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An Approach to Improved Durability Tests for Building Materials and Components

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AN APPROACH TO IMPROVED DURABILITY TESTS FOR BUILDING MATERIALS AND COMPONENTS

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ABSTRACT

Durability tests usually provide relative measures of the time building materials and components will perform their intended functions under the expected service conditions. This is not adequate to ensure the proper selection of new building materials and components because quantitative measures of long-term performance are needed. Although many tests have been developed to accelerate degradation processes of building materials, they are seldom fully adequate for reliably predicting long-term performance. In this paper, a recommended practice, ASTM E 632-78, which provides a framework for the development of improved durability tests, is outlined. The application of the recommended practice, which does not specify an analysis procedure, is illustrated by examples from the literature using both deterministic and probabilistic approaches.

While probabilistic concepts have not been applied extensively to materials durability problems in the construction industry, these concepts offer new opportunities for obtaining improved quantitative predictions of the service life of building materials.

Keywords: Accelerated aging tests; building components; building materials; durability; life testing; prediction; recommended practice; reliability service life.

1. INTRODUCTION

New building components and systems are constantly being designed and manufactured to satisfy the ever-growing needs of society. Many of these components will be subjected to adverse conditions over their life and these adverse conditions can affect their ability to perform as intended. Since materials are the fundamental building blocks of components and systems, it is essential that appropriate materials be selected if the components and systems are to perform their intended functions when initially installed and over their expected service lives.

Building materials usually fall into one of two categories - traditional materials and innovative materials engineered for a particular application. With materials of either category, the operating and stress[1] conditions to which they will be subjected are difficult to predict; therefore, it is difficult to predict how the materials will perform in service. It is essential that a reliable prediction of long-term performance (durability) of a material be made, however, prior to its incorporation into a structure.

There are many definitions of durability. Two used by ASTM committees are:

> Durability is the safe performance of a structure or a portion of a structure for its expected design life. (From ASTM Standard E 241).
>
> Durability is the capability of maintaining the serviceability of a product, component, assembly or construction over a specified time (From ASTM Standard E 632)

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[1] Stress, as used here, is any factor (mechanical, thermal, environmental, or biological) which causes a material to degrade over time.

where serviceability is the capability of a building product, component, assembly or construction to perform the function(s) for which it is designed and constructed (from ASTM Standard E 632).

Both definitions of durability incorporate the concept of design requirements being met or exceeded for a specified period of time -- usually the design life of the system. These definitions also suggest criteria which can be used to measure the adequacy of a particular durability analysis procedure. The optimal procedure should:

1. Give a quantitative estimate of the time to failure of a component or material, when it is exposed to the expected operating conditions. This estimate can be derived from either in-service performance tests or from accelerated aging tests. An <u>accelerated aging test</u> is a test in which the performance of a component at in-service stress levels is predicted from its performance at higher than normal stress levels.
2. Give results which correlate with in-service performance.
3. Identify the degradation mechanisms causing failures at high and low stress levels. For accelerated aging tests, this is necessary to ensure the validity of extrapolating high stress level results to normal or low operating stress levels.

Confidence that a material or component will perform as expected for a specified time is essential to the designer of a building. Confidence in the performance of traditional materials in the normal range of environments can be based on past experience, but it is difficult to establish the same confidence in the performance of innovative materials, or

of traditional materials in environments outside the normal range of experience, e.g., solar and nuclear energy applications. However, unless methods for providing the confidence at an acceptable cost can be established, a severe barrier to innovation will continue to exist. Marshall and Ruegg [1], for example, point out that a major impediment to calculating life cycle costs and savings is that such calculations require life-cycle data on performance, durability, and dependability which is seldom available.

Interest in the prediction of durability is not new and it is not confined to the building industry. The importance of predicting durability has grown rapidly but, unfortunately, the state of durability testing is disorganized as has been pointed by Masters et al. [2]. Although many durability tests are described in standards and specifications for building materials [3], there is seldom a fully satisfactory way of correlating, with each other or with in-service performance, the results of laboratory tests on different materials. The increasing pressures for innovation in the building industry increase the need for development of a systematic approach to evaluation of durability. This need is indicated in the proceedings of the joint RILEM-ASTM-CIB Symposium on the Performance Concept in Buildings [4].

The following shortcomings of standard durability tests can be highlighted:

1. Methods are not usually provided for correlating laboratory results with in-service results.

2. Provisions are usually not made for taking into account different applications of a material or component.
3. In the laboratory, materials and components are usually tested in configurations far different from in-service configurations, making correlations between accelerated aging tests and in-service performance uncertain.
4. Recommendations are seldom made as to how the results of standard tests for different materials should be compared with each other.
5. Quantitative estimates of time to in-service failure are seldom made. The reason is that most standard durability tests are comparative tests; that is, the experimental procedure only allows for the comparison of the durability of an unknown material or component against the performance of a reference material or component, both exposed to identical stresses.
6. The degradation mechanisms of materials and components are complex and not well understood so that it is difficult to design meaningful accelerated tests.
7. The factors affecting service life are numerous, as indicated in Table 1,[2] and difficult to quantify. Thus, many existing tests do not include all factors of importance and factors that are included are seldom related quantitatively to in-service exposure conditions.

Due to the deficiencies in the current technology of durability testing, ASTM subcommittee E 6.22 was formed in 1974 to provide a more general and

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[2] Table 1 is located at the end of this report, on page 29.

improved approach to durability testing. Specifically, its purpose was "the development of methodologies, the dissemination of knowledge, and the stimulation of research relating to the prediction of the service life of building components, and the demonstration of compliance with durability performance requirements". The work of the subcommittee recently led to the publication of the Recommended Practice for Developing Short-Term Accelerated Tests for Prediction of the Service Life of Building Components and Materials, ASTM E 632-78, which is based upon National Bureau of Standards (NBS) research. The practice outlines the process of developing tests to predict the service life of a building material or component from the results of short-term tests. In making a prediction of the time to failure, the procedure emphasizes the necessity of knowing as much as is practical about the nature of the item and the service conditions, e.g., material degradation mechanisms and in-service exposure conditions. It leaves open, however, the details as to which tests should be used and and how the information should be analyzed.

In durability evaluation, the procedures used to measure degradation and to analyze the durability data are very important, for durability research is expensive in terms of money, time, equipment and space, and seldom yields more than a small amount of data. There are two classes of procedures for determining in-service life -- deterministic (e.g., fracture mechanics) and probabilistic (e.g., reliability). In reality, the separation is not distinct, for deterministic procedures often use statistical methods for analyzing their data and probabilistic procedures often use a materials justification in selecting a life distribution.

The obvious advantage in using a deterministic procedure is that the problem is addressed in terms of material parameters. Unfortunately, few, if any, have been successful in modeling the durability of a material. One possible reason for this failure is that deterministic procedures usually model a material in terms of one failure mechanism whereas, in fact, failures over time are usually the result of several time-dependent failure mechanisms [5]. Also, failure mechanisms which cause time-dependent failures are difficult to identify, for the failure is thought to be initiated at the microscopic or submicroscopic level. The inability to observe the initiation of failure and to predict the time of failure for a stressed material led to the belief that durability research could be analyzed in terms of random events [6, 7]; hence the use of probabilistic procedures. The basis for this is the observation that two or more specimens, which appear to be identical, can have failure times which are several decades apart, even though they are subjected to the same stress and operating conditions. The analysis of such random events is within the domain of probabilistic procedures, especially those which address the problem in terms of the material parameters.

2. THE RECOMMENDED PRACTICE FOR DEVELOPMENT OF ACCELERATED SHORT-TERM TESTS FOR THE PREDICTION OF SERVICE LIFE

The recommended practice for developing short-term tests for the prediction of service life described in ASTM E 632 is summarized by the chart in Figure 1. The chart indicates a sequence of steps which we recommend be undertaken in developing and applying tests for predicting the service lives of innovative building materials or components; or existing ones which are to be used under conditions outside their normal ranges.

For convenience, the practice is divided into four parts: 1) Problem Definition; 2) Pre-Testing; 3) Testing; and 4) Interpretation and Reporting of Data. In Part 1, referring to the numbered boxes in the chart, the first step (step 1) is to define the performance requirements to be met by the material or component in service and to set minimum requirements the material or components must meet to be judged serviceable. These criteria provide an objective basis for recognizing when failure has occurred. It should be noted that the failure criteria for a material can change with the application. In step 2, if the material or component is not homogeneous, it should be characterized as thoroughly as possible in terms of the individual materials contained within it and the interfaces between the individual materials. This information is important for gaining insights into the possible degradation mechanisms so that the most appropriate tests can be selected. It should be noted that, because of synergistic effects, composites can have durabilities and properties far different from those of the constituents. The critical performance characteristics are specified in step 3; these characteristics will be used in delineating the limiting condition below which the material or component is deemed unserviceable. In step 4, the expected range of degradation factors, including weathering, biological, stress, incompatibility and use factors, should be identified to help define the conditions to which the material or component is likely to be exposed in service. Synergistic effects between degradation factors can be identified. With this knowledge it may be postulated (step 6) how the degradation processes can be accelerated. If degradation processes can be accelerated without changing the mode of failure, then laboratory test time can be reduced.

Once the experimental procedure has been determined, the performance requirements for the test specimens should be stated (step 7). It must be recognized that much of the knowledge desired may not always be available. In such cases, assumptions based on the best available experience should be made and recorded.

When Part 1 is completed, Part 2, Pre-testing, can be initiated (step 8 in Figure 1).[3] Its purpose is to demonstrate that rapid failures can be caused by intensifying the degradation factors specified in Part 1. These preliminary experiments provide the background for Part 3 which begins with the establishment of more realistic accelerated aging tests (step 9). These accelerated tests should be conducted at different stress levels. At the same time (step 10), long-term tests under in-service conditions should be initiated. The results of long-term tests provide the most convincing evidence that the results of accelerated aging tests can be extrapolated to in-service conditions. They are important in insuring that second order effects are not causing the failure at low stress levels. If second order effects appear to be causing the failures, then the accelerated test conditions should be reviewed to determine whether factors which accelerate second order effects are too severe or whether important degradation factors have been omitted.

If the results of the accelerated tests and the long-term tests are consistent with each other, Part 4, Interpretation and Reporting of Data, can be undertaken. This includes use of experimental data to predict the course of degradation under expected in-service conditions (step 13) and to predict the time at which failure, as defined by the performance criteria, will

[3] The figures are located at the end of this report, beginning on page 30.

occur (steps 14 and 15). The performance criteria for failure in the predictive service life tests may differ from those of the in-service tests because of different specimen configurations and nonlinearity of response to degradation factors. The practice concludes with the reporting of data (step 16) in which, it must be emphasized, all assumptions should be made clear.

The ASTM recommended practice recognizes that:

- Although it is desirable to have complete data on the material or component, the conditions to which it is to be exposed and the degradation mechanisms, assumptions about these will often have to be made to keep within the constraints imposed by time and funding.

- The predicted service life of a material or component will depend upon the range and intensity of the degration factors to which it is exposed in service and the choice of the failure criteria.

- Because possible errors in the predictions can vary widely, it is important that possible sources of error should be identified and an attempt made to assess their magnitude.

As an aid to the application of the recommended practice, the attention of the user is drawn to a list (Table 1) of degradation factors which may affect the performance of building materials and components. In any application, it is recommended that a matrix, similar to that in Figure 2, be made to aid in identifying properties of importance.

3. EXAMPLES TO ILLUSTRATE THE APPLICATION OF THE RECOMMENDED PRACTICE

The recommended practice is independent of the analysis procedure, i.e., it provides a framework for analysis. The two broad classes of analytical procedures -- deterministic and probabilistic -- both readily adapt to the format of the recommended practice. The two procedures differ in how they obtain an answer to the basic question asked of durability test results. Before differentiating between the two procedures, however, an understanding of the questions that durability tests should answer must be developed.

As mentioned in the introduction, the procedure used to analyze the durability test results should have several attributes. It is particularly important that criteria for failure be established. For most building materials exposed to given environmental conditions, the time to failure of interest is that time beyond which an unacceptable number (percent) of failures occurs. For a non-critical component, for example, the user of the component might be willing to allow ten percent of a nominal population of components to fail prior to the expected design life of the structure. For critical components, however, one failure in a thousand might be the maximum allowed. The difference between deterministic and probabilistic procedures lies in how the estimates of these low probable times to failure are made.

Deterministic procedures first obtain estimates of the expected time to failure under a given set of operating conditions. Once this expected time to failure is obtained, an estimate at a low percent failure is derived by dividing this expected time to failure by an appropriate reduction factor. Since these reduction factors have little or no statistical significance, the time to failure which results from their use gives only a qualitative

measure of assurance that few in-service failures will occur. That is to say, reduction factors only permit the statment to be made that the probability of an in-service failure of a component is low whereas, optimally, a statement as to what percent of a nominal population will fail prior to a given time is needed. A quantitative estimate gives the researcher a basis by which he can test for a significant difference between the times to failure of two different nominal populations of materials. Using the time to failure distribution for a given material, reliability analysis provides a quantitative estimate of the time at which a designated low percent of a nominal population will have failed; hence, it provides a methodology to measure significant differences in two nominal populations of material.

In the examples which follow, the first uses a deterministic approach and the second uses a reliability approach. The second is not taken from the construction industry because no good examples of application of the reliability approach are available. The third example concerns coatings and it shows how the recommended practice will be used to aid the planning of one of our own projects.

3.1 EXAMPLE NO.1 - THE RESISTANCE OF A CONCRETE STRUCTURE TO FREEZING AND THAWING

The first example of a possible application of the ASTM recommended practices is based on a portion of a paper by Plum, Jessing, and Bredsdorff [8]. It emphasizes understanding the degradation mechanisms and the development and application of mathematical models. The procedures used by the authors follow closely the steps prescribed in the recommended practice. Their case was a hypothetical one in which a specific concrete structure would be exposed to freeze-thaw cycles.

The implicit objective of the study was to determine the expected life for each element of the structure. Referring to the steps of Figure 1, our interpretation of their approach is as follows.

Step 1. Performance Requirements and Failure Criteria - The requirement for any element is that the concrete strength should be adequate for the structure to perform as intended. The failure of an element occurs when the strength of the element falls below an acceptable value.

Step 2. Characterization of the Material(s) - The chemical, physical, and macro- and micro-structural characteristics of the material are determined from the known ingredients of the concrete, the mix design, and the curing conditions.

Step 3. Critical Performance Characteristics - The critical performance characteristic for each element is the compressive strength. The compressive strength can be used as an indicator of degradation.

Step 4. Expected Type and Range of Degradation Factors - The only degradation factor considered is the freezing of water-saturated concrete. Much information is needed about the range of temperatures, including minimum temperature, frequency of freeze-thaw cycles, rates of cooling, and duration of periods below 0°C, but this can be obtained, or estimated, from meteorological data.

Step 5. Possible Degradation Mechanisms - The only degradation mechanism judged to be important is fatigue resulting from internal stresses associated with the cyclic freezing and thawing of water within the pores of the concrete.

Step 6. Postulate Methods of Causing Accelerated Aging Similar to Aging in Service - Carry out frequent freezing and thawing of concrete with a high degree of water saturation.

Step 7. Performance Requirements for Predictive Service Life Tests - The predictive tests should produce a loss of strength of the concrete by the same mechanism as observed in actual service. The tests should yield results in relatively short times and the severity of the test conditions should be able to be changed easily to facilitate study of the effects of changing the conditions.

Step 8. Design and Perform Predictive Tests to Cause Rapid Failure and Confirm Degradation Mechanisms - Using temperature changes from meterological data as a guide, concrete specimens with saturation coefficients, S, greater than 0.92 are subjected to rapid cooling freeze-thaw cycles. The loss of strength is measured as a function of the number of freeze-thaw cycles.

Step 9. Extend the Tests of Step 8 to Less Severe Conditions to Establish the Relationships Between Severity of Conditions and Rate of Degradation - Keeping S above 0.92, lower the frequency of cycling and lower the cooling rates. Tests with values of S less than 0.92 were judged to be unnecessary because of previously published evidence that freeze-thaw damage is negligible at lower S values.

Step 10. Long-Term Tests Under Service Conditions - Long-term tests are not mentioned by Plum et al. They appeared to believe that, from the results of accelerated tests carried out under a wide range of conditions,

a performance model could be developed which would be satisfactory in predicting behavior under all likely circumstances. Also, prior experience on the freeze-thaw behavior of concrete and information in the literature can help in assessing the realism of the accelerated tests. (In our view, long-term tests should almost always be started even though it is uncertain whether they will give much information in the time available).

Step 11. Compare the Types of Degradation Obtained in Service and in the Predictive Service Life Tests - Such a comparison is not mentioned explicitly. However, the authors discuss procedures for extrapolating the results of accelerated tests to in-service conditions.

Step 12. Is the Degradation Obtained in the Predictive Tests of the Same Nature as in the In-service Tests? - This is not commented upon explicitly but it is clear the authors believe that their proposed experiments could meet this condition.

Step 13. Develop Mathematical Models of Degradation and Compare the Rates of Change in Predictive Tests with In-service Tests - The authors believe that the complex mechanistic models they outline could be developed to cover the whole range of likely exposure conditions using the data obtained from the predictive tests of steps 8 and 9. (The authors noted that the models would have been too complex to use with the computers available to them at the time this research was performed).

Step 14. Performance Criteria for Predictive Service Life Tests - The criterion for failure appears to be the same as for in-service tests (see step 1).

Step 15. Predict Service Lives - The models from step 13 should be applied to each portion of the concrete structure to predict the time to failure under typical exposure conditions as defined in step 4.

Step 16. Report the Data - The authors do not comment on the reporting of the data or on the importance of stating the assumptions and the estimates of error. (If studies such as those they describe were actually carried out, it would, of course, be essential to comment on the reliability of the predictions and state the assumptions and approximations made so as to minimize the possibilities for misunderstanding).

It may be inferred from this example that the prediction of service life may be very complicated if knowledge (or assumptions) about the details of degradation processes is to be incorporated in a mathematical model. The need for such a model was lessened in the case of Example 1 because of the possibility of confirming directly that the accelerated tests caused degradation similar to that observed in the long-term tests. We consider it axiomatic that predictions of service life should be based on the best possible knowledge of the degradation mechanisms of the objects in question and the environments to which they are likely to be subjected.

3.2 EXAMPLE NO. 2 - STATISTICAL ANALYSIS OF THE FATIGUE LIFE OF DEEP-GROOVED BALL BEARINGS

The second example selected to demonstrate the applicability of the recommended practice is from one of the first published papers using reliability theory to solve a practical problem [9]. It concerns ball bearings. We would have liked to have been able to use an example from building

materials technology but we do not know of any which is satisfactory for our purpose.

The objective of the study, which was carried out by Lieblein and Zelen, was to determine the dynamic capacity for a nominal population of deep-grooved ball bearings. Dynamic capacity is the load at which 90% of the nominal population will survive when subjected to one million stress cycles. Dynamic capacity is used by the ball bearing industry to rate one nominal population of ball bearings against another. Lieblein and Zelen's task was to probabilistically analyze already available data using an accepted equation.

Using Figure 1, our interpretation of Lieblein and Zelen's analysis is as follows:

Step 1. Performance Requirements and Failure Criteria - The function of ball bearings is to prevent machine parts from deviating from a desired direction. Failure of a ball bearing usually results from ball bearing fatigue, the incipient stage is the formation of a fatigue crack. Failure occurs when a crack propagates and a piece of the race or ball spalls out. For this study, all ball bearing failures were assumed to have occurred in this way.

Step 2. Characterization of the Material - The dynamic capacity for a nominal population of ball bearings is a function of the following factors: the number of balls, the diameter of the balls, the number of rows of balls, the angle at which the balls are stressed (the contact angle), the type of material used (balls, raceway, and cage), the type of metal processing, and finally, the type of lubricant.

Step 3. Critical Performance Characteristics - The characteristic used to measure the failure of a ball bearing was either total failure of the ball bearing causing spalling out or a change in the performance of the ball bearing (increased friction or excessive horsepower).

Step 4. Expected Type and Range of Degradation Factors - Some of the factors which tend to reduce the life of a nominal population of ball bearings are the applied load, the type of loading (uniform or non-uniform), the speed at which the bearings revolve, and the operating temperature. The range for each of these factors must be determined from expected in-service operating conditions.

Step 5. Possible Degradation Mechanisms - Deep grooved ball bearings can fail from wear-out or lubrication failure. As Burwell [10] points out, wear-out can be classified into four categories -- adhesive or galling wear, abrasive or cutting wear, corrosive wear, and surface fatigue. For this study, all failures were considered to be fatigue failures.

Step 6. Postulate Methods of Causing Accelerated Aging Similar to Aging in Service - Unlike many other industries manufacturing materials or systems, the ball bearing industry has extensive empirical information on the fatigue lives of ball-bearings. From this data an equation showing the interrelationships between the factors influencing the life strengths of ball-bearings was developed. This equation, called the Lundberg-Palmgren equation, is expressed [9] as

$$L = \left\{ \frac{f_c Z^{a_1} D^{a_2} (i \cos \alpha)^{a_3}}{P} \right\}^p \qquad (1)$$

where

Z = number of balls

D = ball diameter

i = number of rows of balls

α = contact angle

P = bearing load

L = number of revolutions that a specified percent of bearings will fail to survive when subjected to fatigue

and p, a_1, a_2, a_3, and f_c are unknown parameters. Since $\alpha = 0°$ for deep grooved ball bearings, the above formula is greatly simplified.

Life tests for ball bearings are usually accelerated by an increase in the applied load. Other methods which have been used to accelerate life tests include changes in the lubricant and changes in the operating speed.

Step 7. Performance Requirements for Predictive Service Life Tests - Historically, time to failure data from bench tests have been shown to be good predictors of in-service test results. These results are usually obtained by loading the ball bearing with a known stress and then obtaining an estimate of dynamic capacity. As Shaw and Macks [11] point out, however, in-service tests should also be conducted.

Step 8. Design and Perform Preliminary Tests to Cause Rapid Failure and Confirm Degradation Mechanisms - Since the interrelationships between variables was already established via Eq. 1, this step is not necessary except when new applications are involved (e.g., ball bearings being used in high-speed aircraft, missiles, etc.). Since new applications were not considered, Eq. 1 was used.

Step 9. Extend the Tests of Step 8 to Less Severe Conditions to Establish the Relationships Between Severity of Conditions and Rate of Degradation or Loss of Performance - The data Lieblein and Zelen analyzed came from four different ball bearing companies. The range of stresses was wide enough for Lieblein and Zelen to determine the rate of degradation at different stress levels.

Step 10. Long-Term Tests Under Service Conditions - Lieblien and Zelen did not carry out long-term tests under service conditions. They assumed that Eq. 1 was correct.

Steps 11 and 12. Compare Types of Degradation Obtained in Service and in the Predictive Service Life Tests - The authors state that one of their initial assumptions was that life test degradation was similar to degradation in-service. This assumption appears to be a good one, since it is still used [12].

Step 13. Develop Mathematical Models of Degradation and Compare the Rates of Change in Predictive Tests with In-service Tests - Lieblien and Zelen chose the Weibull life distribution to model the life length for ball bearings exposed to a constant stress. The choice of the Weibull distribution was

made because it is a limiting distribution for minimum times to failure and because it appeared to fit the life data well.

Step 14. Performance Criteria for Predictive Service Life Tests - Spall out or race failure are commonly used in-service failure criteria.

Step 15. Predict Service Lives - The authors did not do this since they were more interested in determining the dynamic capacity of the material. It is obvious, however, that if Eq. 1 is correct and a constant in-service stress condition could be assumed, then the number of stress cycles such that 90% of the specimens will survive could easily be computed for any applied stress.

Step 16. Report the Data - The authors explicitly state the assumptions used in deriving their test results.

3.3 EXAMPLE No. 3 - DEVELOPMENT OF TESTS FOR CORROSION-PROTECTIVE COATING SYSTEMS FOR STEEL STRUCTURES

The stepwise application of the recommended practice to a coating system for protection of steel structures against corrosion [13, 14] is used as the last example. The term "coating system" includes the surface preparation, the coating material, and the methods and environment used for application and curing. A typical problem to be addressed is the selection, from many possible paint systems, those coating systems which will survive, with 90% probability, fifteen or more years of in-service use. Using the recommended practice, a possible approach includes the following steps.

Step 1. Performance Requirements and Failure Criteria - The coating system is required to protect the steel, including welds and other joints, from rapid corrosion for 15 years in the environments to which it is to be exposed. One criterion of failure might be that the coating system will be considered to have failed when there is visible evidence of rusting over at least 5% of the surface area or over 10% of the length of welds. The exact criteria adopted will depend upon the application, but the criteria should be quantitative and reflect the best available knowledge and experience.

Step 2. Characterization of the Material (s) - The systems will consist of paints of known generic types applied to prepared steel surfaces under a range of environmental conditions. The paint films will be classified with respect to type and volume of resin, solvent, fillers, and plasticizers. Other paint variables which will be measured include the glass transition temperature, molecular weight, modulus of elasticity, and paint thickness.

Step 3. Critical Performance Characteristics - Critical performance characteristics of the coatings are likely to be adhesive and cohesive strengths of the film. Properties that can serve as degradation indicators are appearance, dielectic strengths, molecular weight change, and film modulus.

Step 4. Expected Type and Range of Degradation Factors - Locations where the systems are to be used should be reviewed and those with the most severe exposure conditions identified. The range of exposure conditions to which the coatings will be subjected is determined from meteorological data. Important degradation factors include elevated temperature, temperature cycles, relative humidity, solar radiation, and air pollutants (including salt spray and sulfur dioxide).

Step 5. Possible Degradation Mechanisms - Loss of integrity or loss of adhesion of the coating may result from corrosion of the steel substrate due to migration of oxygen and water vapor through the coating or it may result from high internal stresses. Rates of degradation in terms of increase in permeability to oxygen and water vapor are likely to be a function of coating thickness and coating embrittlement. Loss of adhesion may occur due to growth of rust under the coating, particularly where the surface was contaminated with chlorides or other salts before painting, or where salts permeate through the coating in salt environments.

Step 6. Postulate Methods of Causing Accelerated Aging Similar to Aging in Service - Sets of specimens with features typical of interfaces and joints which occur in field applications should be exposed separately to (i) simulated solar radiation of greater intensity than would normally be expected in-service, (ii) water, (iii) elevated temperatures, (iv) temperature cycles and (v) acidic solutions to simulate the effects of pollutants. Information on synergistic effects of degradation factors should be sought through investigation of combined effects.

Step 7. Performance Requirements for Predictive Service Life Tests - The predictive tests should produce failure by the same mechanisms as in service, but in a much shorter time. The tests should rank the systems in the same order of durability as in-service exposures. The severity of the exposure conditions should be able to be varied easily from one test to the next.

Step 8. Design and Perform Preliminary Tests to Cause Rapid Failure and Confirm Degradation Mechanisms - To confirm degradation mechanisms for each coating system, samples should be prepared under a range of demanding conditions simulating those likely to be occur in service, e.g., painted joints, rough surfaces or contaminated surfaces, coating of various thicknesses, and different application techniques. Specimens should be exposed to accelerated aging conditions including ultraviolet radiation, high relative humidity, condensing moisture (with and without dissolved air pollutants), temperature aging, temperature cycling, and combinations of these. If any experiment shows evidence of unusually rapid coating degradation, a decision must be made as to whether to drop the system from further consideration or to carry out tests under less severe conditions as in Step 9. This would be to determine if the severe conditions had induced degradation by a mechanism which would not normally be important in service.

Step 9. Extend the Tests of Step 8 to Less Severe Conditions to Establish the Relationships Between Severity of Conditions and Rate of Degradation or Loss of Performance - The exact conditions of test would depend upon the rates of degradation observed in Step 8. Emphasis would be on those degradation factors, and combinations of factors, judged most likely to cause failure in service.

Step 10. Long-Term Tests Under Service Conditions - Comparison samples of coated steels similar to those studied in Steps 8 and 9 should be placed in outside exposures judged to be representative of those encountered in-service. Actual exposure of coatings on steel structures are useful in determining the adequacy of the proposed models.

Step 11. Compare the Types of Degradation Obtained in Service and in the Predictive Service Life Tests - Although this comparison may not be useful unless detectable degradation occurs in the time available for the long-term tests, the comparison should always be made. Visual observation may be all that is required but more careful observation with the light and scanning electron microscopes will probably be desirable.

Step 12. Is the Degradation Obtained in the Predictive Tests of the Same Nature as in the In-service Tests? - The evidence from Step 11 will be evaluated to see if, for any of the coating systems, there is any suggestion of a difference in degradation mechanisms between the accelerated and long-term tests. For any system for which there is a difference, it is probable that the exposure conditions in the accelerated tests were too severe to be realistic so that the tests should be repeated under less severe conditions if the systems are still of interest. For the others, Step 13 can be undertaken.

Step 13. Develop Mathematical Models of Degradation and Compare the Rates of Change in Predictive Tests with In-service tests - From the data in Steps 8, 9, and 10, models or mathematical relationships capable of accounting for all the available data should be developed. To the extent possible, they should include consideration of failure mechanisms and of behavior under individual degradation factors and combinations of factors.

Step 14. Performance Criteria for Predictive Service Life Tests - The performance criteria for failure in the predictive in-service life tests will probably be similar to those for the in-service performance or long-term tests.

Step 15. Predict In-service Lives - The model for each coating system will be used to predict the service life under the various conditions of interest.

Step 16. Report the Data - The results will be reported in as much detail as possible with clear statements of the assumptions made and their implications for the reliability of the service life predictions.

Systems which, according to the predictions, meet the desired performance requirements stated in Step 1 should be identified.

The work outlined in this example would be extensive and would have to be carefully planned to ensure that the accelerated tests simulate in-service conditions; the plan should minimize the possibility of overlooking important degradation factors which might adversely affect the performance of the system.

4. SUMMARY AND CONCLUSIONS

New materials and components are constantly being introduced to help meet societal needs. These new materials, along with more traditional materials, are used in applications for which little or no *a priori* knowledge exists on how they will perform in service. For this reason, there exists a need for standardized, accelerated durability tests which are capable of predicting in-service performance for a given material when used in a specified application.

Although there are many published durability tests, they are seldom adequate for predicting long-term performance in-service. Part of the reason for this inability to predict in-service performance results from the use of tests

which have little or no bearing on the intended material application. The framework provided by ASTM E 632 can aid in meeting the need for improved durability test procedures. Such a framework is particularly important in insuring that the researcher considers all aspects of the problem in designing and carrying out research.

Although ASTM Method E 632 does not specify an analysis method, the principles of reliability analysis have been successfully utilized in addressing a number of durability-related problems. While reliability concepts have not been applied extensively to materials durability problems in the construction industry, the authors conclude that the concepts offer new opportunities for obtaining quantitative predictions of the service life of building materials.

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TABLE 1. DEGRADATION FACTORS AFFECTING THE SERVICE LIFE OF BUILDING COMPONENTS AND MATERIALS

- Weathering Factors
  - Radiation
    - Solar
    - Nuclear
    - Thermal
  - Temperature
    - Elevated
    - Depressed
    - Cycles
  - Water
    - Solid (such as snow, ice)
    - Liquid (such as rain, condensation, standing water)
    - Vapor (such as high relative humidity)
  - Normal Air Constituents
    - Oxygen and ozone
    - Carbon dioxide
  - Air Contaminants
    - Gases (such as oxides of nitrogen and sulfur)
    - Mists (such as aerosols, salt, acids, and alkalies dissolved in water)
    - Particulates (such as sand, dust, dirt)
  - Freeze-thaw
  - Wind
- Biological Factors
  - Microorganisms
  - Fungi
  - Bacteria
- Stress Factors
  - Stress, sustained
  - Stress, periodic
  - Stress, random
    - Physical action of water, as rain, hail, sleet, and snow
    - Physical action of wind
    - Combination of physical action of water and wind
    - Movement due to other factors, such as settlement or vehicles
- Incompatibility Factors
  - Chemical
  - Physical
- Use Factors
  - Design of system
  - Installation and maintenance procedures
  - Normal wear and tear
  - Abuse by the user

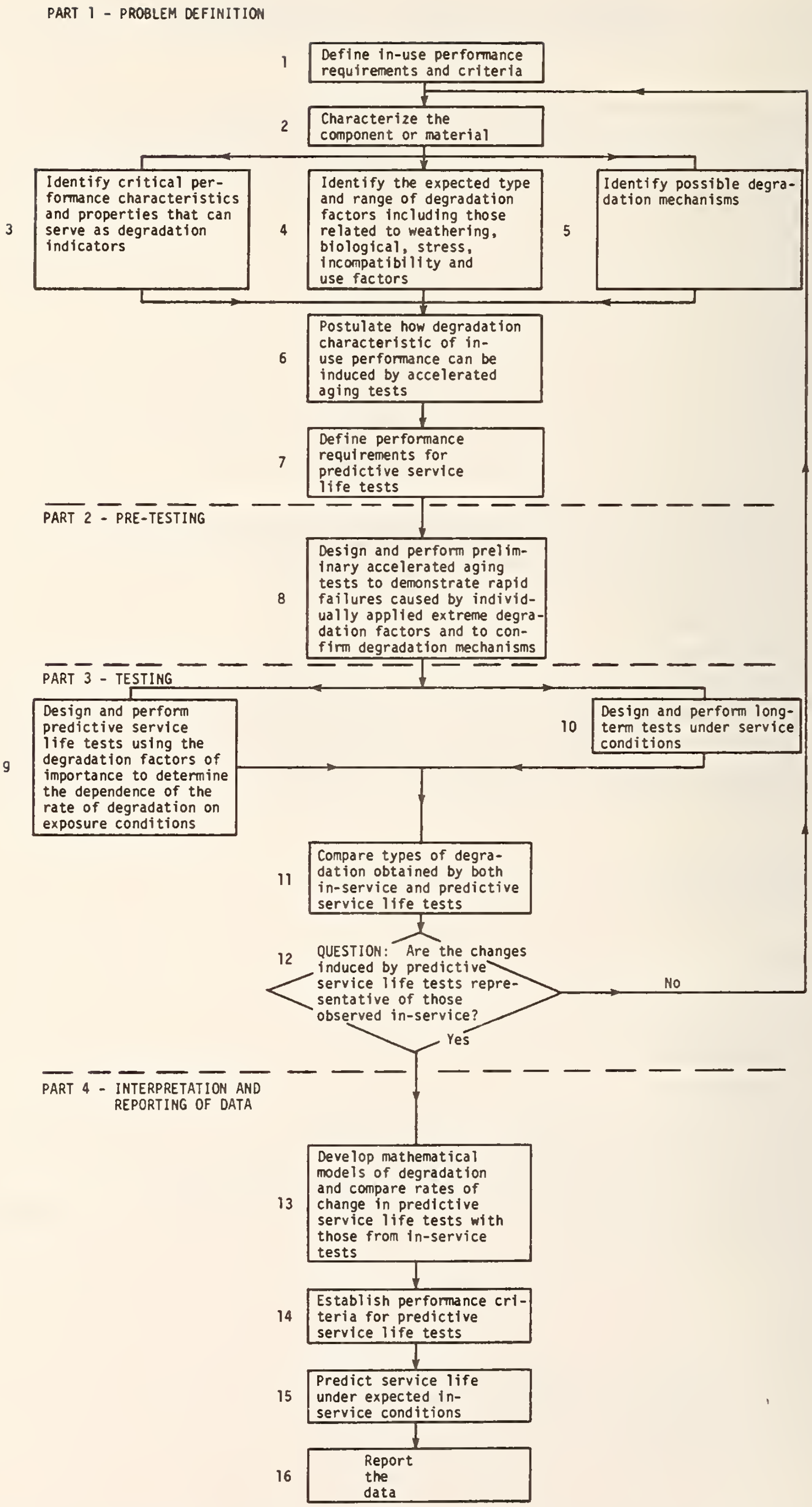

Figure 1. Steps in the Recommended Practic for Developing Predictive Service Life Tests

OBSERVABLE CHANGE / BUILDING ELEMENT	VISUAL INSPECTION											MEASURED CHANGE																												
	MICRO-ORGANISMS GROWTH	GENERAL APPEARANCE	CHALKING	CRAZING	CRACKING	CHECKING	FLAKING	SEALING	BLISTERING	EFFLORESCENCE	RUPTURE	COLOR	GLOSS	REFLECTANCE	HAZE	TEXTURT	TRANSPARENCY	ABRASION RESISTANCE	HARDNESS	WASHABILITY	SURFACE WETTABILITY	WATER ABSORPTION	VAPOR PERMEANCE	DIMENSION	THERMAL PROPERTIES	ELECTRICAL PROPERTIES	CREEP RUPTURE	CREEP DEFORMATION	PEEL STRENGTH	FLEXURAL STRENGTH	TEAR STRENGTH	IMPACT RESISTANCE	FATIGUE STRENGTH	TENSILE STRENGTH	COMPRESSIVE STRENGTH	SHEAR STRENGTH	TENSILE MODULUS	COMPRESSIVE MOD.	SHEAR MODULUS	ADHESION
A																																								
A-B																																								
B																																								
B-C																																								
C																																								
⋮																																								

Let A represent either the exterior-most or interior-most element

Let A-B, B-C, etc. represent interfaces between elements

Figure 2. Example of a Matrix for Identifying Observable Changes of Building Components and Materials

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Durability tests usually provide relative measures of the time building materials and components will perform their intended functions under the expected service conditions. This is not adequate to ensure the proper selection of new building materials and components because quantitative measures of long-term performance are needed. Although many tests have been developed to accelerate degradation processes of building materials, they are seldom fully adequate for reliably predicting long-term performance. In this paper, a recommended practice, ASTM E 632-78, which provides a framework for the development of improved durability tests, is outlined. The application of the recommended practice, which does not specify an analysis procedure, is illustrated by examples from the literature using both deterministic and probabilistic approaches.

While probabilistic concepts have not been applied extensively to materials durability problems in the construction industry, these concepts offer new opportunities for obtaining improved quantitative predictions of the service life of building materials.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Accelerated aging tests; building components; building materials; durability; life testing; prediction; recommended practice; reliability service life.

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